Energy Research & Social Science 50 (2019) 18–28

Contents lists available at ScienceDirect

Energy Research & Social Science

journal homepage: www.elsevier.com/locate/erss

Original research article

Envisioning surprises: How social sciences could help models represent ‘deep uncertainty’ in future energy and water demand

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ARTICLE INFO

Keywords:
Demand forecasting
Decision-making
Uncertainty
Paradigm change

ABSTRACT

Medium- and long-term planning, defined here as 10 years or longer, in the energy and water sectors is fraught with uncertainty, exacerbated by an accelerating ‘paradigm shift’. The new paradigm is characterised by a changing climate and rapid adoption of new technologies, accompanied by changes in end-use practices. Traditional methods (such as econometrics) do not incorporate these diverse and dynamic aspects and perform poorly when exploring long-term futures. This paper critiques existing methods and explores how interdisciplinary insights could provide methodological innovation for exploring future energy and water demand. The paper identifies four attributes that methods need to capture to reflect at least some of the uncertainty associated with the paradigm shift: stochastic events, the diversity of behaviour, policy interventions and the ‘co-evolution’ of the variables affecting demand. Machine-learning methods can account for some of the four identified attributes and can be further enhanced by insights from across the psychological and social sciences (human geography and sociology), incorporating rebound effect and the unevenness of demand, and acknowledging the emergent nature of demand. The findings have implications for urban and regional planning of infrastructure and contribute to current debates on nexus thinking for energy and water resource management.

1. Introduction

1.1. Uncertainties facing the water and energy sectors

Urban and regional infrastructures in the energy and water sectors tend to have a long lifespan. For this reason, strategic infrastructure-related planning has long-term consequences, shaping the systems of provision and demand patterns for decades ahead. Strategic planning is often enacted in conditions of uncertainty related to political, economic, social, technological, legal and environmental factors, commonly abbreviated as ‘PESTLE’. While uncertainty is inherent in long timeframes, a ‘paradigm shift’ is ushering in new uncertainties, with the provision of water and energy being among the resources affected [1,2]. This ‘paradigm shift’ refers to a radical change in some of the PESTLE aspects (particularly environmental, social and technological) over the lifetime of infrastructures, giving rise to uncertainties not considered previously. The shift is driven by a combination of dynamic factors and interactions, including uncertainties about worsening climatic impacts on resources and infrastructure, an increasing probability of tipping points in the climate system, rapid adoption of new technologies, societal responses to both climate change mitigation and impacts, and wider changes in patterns of resource use.

These dynamic factors display the characteristics of ‘deep uncertainty’. In the context of long-term decision-making, the definition of deep uncertainty includes three elements: uncertainty about variables and their probability distributions; uncertainty about the interactions between those variables; and uncertainty about the consequences of alternative decisions [3]. This definition of deep uncertainty captures some of the challenges infrastructure operators face when considering long term investments in their assets and assessing how future demand may evolve. Many future-exploring methods rely on historic trends and relationships which may no longer hold throughout this ‘paradigm shift’. Accordingly, it is important to consider how these complex systems can be explored methodically to develop integrative approaches

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https://doi.org/10.1016/j.erss.2018.11.008
Received 13 December 2017; Received in revised form 29 October 2018; Accepted 22 November 2018
Available online 30 November 2018

reflecting their complexity. This paper follows Cilliers [4] in avoiding a single definition of complexity, which would be inherently reductionist, and in identifying several attributes of complexity instead.

In this paper, the emphasis is placed on studies using 10-year and longer horizons defined here as a medium to long term – merging the two temporal scales since both are important for strategic planning. These horizons are relevant to contemporary strategic planning for two main reasons. Firstly, due to lock-in [5], decisions on infrastructural investment made today will influence demand/supply systems several generations into the future. Energy and water infrastructures in particular can last up to a hundred years [6–9]. Secondly, significant climate change impacts are likely to become more apparent towards the end of the century [10,11]. The long lifespan of assets means that they need to be robust to climatic changes to avoid supply shortages [12,13].

Considering future uncertainties within water resources management, there are concerns about the significant changes to the hydrological cycle [14,15] and to how water resources interact with an evolving population and other social, political, cultural and technological changes [16–18]. In the energy sector, resource availability and infrastructure are affected by the potential decentralisation of energy supply and decarbonisation of the fuel mix [2], including renewable technologies that are intermittent and weather-dependent [19]. Both sectors are also dealing with the need to modernise decaying urban and regional infrastructure [8,20], to make traditional infrastructures resilient to a changing climate [12,13,21–23], and to develop new decentralised infrastructures such as renewable technologies or water-sensitive cities [24–28].

1.2. Applying nexus thinking across the sectors

Putting aside other elements of the nexus (*e.g.* food and land), this study focuses on future demand in energy and water sectors in industrialised contexts, as these two sectors share specific characteristics that shape long-term planning. For example, both are resources typically provided by public utilities; both have historically needed major network infrastructure development to meet demand; and for both, particularly at a household level, everyday practices underpinning demand intersect, such as in the case of hot water used for laundry or showering, cooking and cleaning. Consequently, when it comes to strategic planning, the issues faced by decision-makers in the two sectors share similarities and overlaps, but tend to be governed separately [29].

With the interconnections between energy and water resources being increasingly recognised [30], both decarbonisation and climate change would have systemic impacts across the two sectors. For instance, the installation of carbon capture and storage on coal-fired power plants would increase overall water demand, while climate change exacerbates water stress [31–33]. For both water and energy, the impending changes in demand and supply are complicated by social, economic, environmental and technological uncertainties at a range of scales: from individuals and households to international and global levels.

While some degree of uncertainty is unavoidable, in the past five years there have been numerous calls for 'nexus' thinking to clarify these interlinked uncertainties and complexity [34–39]. In the UK and internationally this is reflected in a range of conferences[1] and funding calls aimed at exploring the water-energy-food nexus challenge [40–42]. Connected to this programme of work and the burgeoning international profile of research on the water-energy-food nexus, the development of new interdisciplinary, cross-sectoral understanding of energy and water demand is now a strong pillar of the UK Research Councils supporting a number of dedicated multidisciplinary research centres, such as The DEMAND Centre and the Centre on Innovation and Energy Demand [43]. The nexus approach attempts to synthesise insights across knowledge domains, for example, by integrating the areas of energy and water demand. While there is a proliferation of research funding being directed to these areas, the challenges remain for methodological innovation within the field of energy and water demand—the development of shared languages [44,45] and the integration of methods across ontological divides [46–49]. Through exploring the approaches currently used to understand future demand and their ability to provide insights into the challenges of the 'paradigm shift', this paper contributes to developing new interdisciplinary methods.

This paper explores how future energy and water demand is modelled, using the term modelling to encompass both quantitative and qualitative methods of envisioning future demand, and offers ideas on improving the modelling techniques, as a basis for supporting long-term strategic planning. A range of disciplines are brought together, from across the environmental, psychological and social sciences, to develop a more sophisticated conceptualisation of demand modelling than exists currently. This aim is achieved by, first, establishing four main attributes of deep uncertainty to be captured when modelling future energy and water demand: the diversity of behaviour, stochastic events, policy interventions and the co-evolution of the variables that shape demand. Second, the paper develops a comprehensive typology of methods for exploring future energy and water demand. This new, interdisciplinary, inter-sectoral typology is used to identify and critique areas of current modelling to be improved. It uses, as the basis of discussion, the complexity highlighted by the UK Research Councils and Government. However the findings have salience beyond this national case, as the focus is on industrialised countries in general. Third, based on the conceptual areas for improvement identified in existing methods, the paper offers insights from disciplines (such as psychology, sociology and human geography) currently under-represented in dominant modelling methods, to challenge and enrich the methodological possibilities for understanding future water and energy demand.

2. Existing modelling methods and their treatment of uncertainty

By exploring methods of modelling future demand for water and energy, the paper seeks to identify ways of supporting long-term decision-making regarding infrastructure investments and to contribute to the nexus debate. While not all strategic decision-making in relation to demand depends on modelling future demand—decisions are often based on expert opinions or rules of thumb—it is increasingly used as a way to support planning [50,51]. In this paper, modelling is framed as ways of imagining (not necessarily forecasting) future demand. Such approaches are usually quantitative and use programmable machines, although modelling can also be qualitative in nature or take advantage of mixed methods, and they do not necessarily provide 'one' answer, more often producing a range of plausible representations of future demand [51].

In the past two decades, modelling has experienced its own paradigm shift, with more powerful computing capacity and better availability of input data (such as regional climate forecasts) than in the past. Despite a proliferation of models, few studies explore the totality of modelling methods across both quantitative and qualitative disciplines within the energy-water nexus. The dominance of a particular type of economics is still evident and shapes representations of energy and water futures within policy domains [52,53]. Poor representation of rapid change, of the diversity of practices and behaviour, and of societal responses to uncertainty and change highlight the need for more integrative approaches [1,54–57]. These limitations suggest that demand-side uncertainty is particularly difficult to capture in futures studies (*i.e.* studies that explore futures) when relying solely on mainstream economics. The attempts to deepen interdisciplinary and transdisciplinary demand modelling approaches remain a niche minority, although a range of new approaches are emerging [51,58]. Since

[1] Examples of nexus conferences and events include the *International Conference on Sustainability in the Water-Energy-Food Nexus*, May 2014, in Bonn, Germany; the *Energy Water Food Nexus International Summit*, March 2015, in Florida, USA; and the *Nexus 2018: Water, Food, Energy and Climate*, April 2018, in North Carolina, USA.

addressing the socio-technical complexities of demand-side management is increasingly seen as an essential way to promote a less resource-intensive society [54,59–64], this article discusses how to improve the representation of future demand in modelling to inform strategic planning in the water and energy sectors.

There are many types of uncertainty, depending on whether it is categorised by its location, level or nature [65]. The main types are *parametric* (uncertainty in a model's parameters, or inputs, such as weather forecasts or population projections that have a range of potential future values rather than a single value) and *structural* (uncertainty about whether a model appropriately reflects the real world). Much literature focuses on dealing with parametric uncertainty [66,67], whereas structural uncertainty is less well explored [68,69]. Some ways of dealing with structural uncertainty are experimentation and expert input, where social science insights might be particularly relevant, leading to a truer representation of diverse socio-technical realities in models.

In relation to uncertainty, literature on demand-side modelling identifies a number of limitations that models grapple with, including unusual peak consumption days (such as during football matches or a royal wedding) [70], informal economies and inequalities [71], penetration of renewables [72] and water quality [73]. Additional quantitative data and field measurements would enhance the modelling of energy and water demand; however, qualitative sources of insight such as case studies, expert interviews, and social practice theory are also mentioned as essential and under-used [70,71,74]. As methods used for exploring future energy and water demand strongly affect planning and decisions in these sectors, it is important to continue refining, expanding and improving such methods to ensure relevant and state-of-the-art insights.

3. Methods

The methods used in this study included a literature review, a survey of academic experts and two interdisciplinary expert workshops. Firstly a non-systematic literature review was used to identify attributes of coupled human and natural systems [75,76]. This was followed by a systematic review of typologies of methods for exploring future energy and water demand, to derive an aggregate typology (Fig. 1). The expert survey informed initial development of the typology, including its preliminary structure and suggestions of further literature to consult. An updated typology was then presented to the experts at the workshops who added extra methods (such as multicriteria decision analysis) that they thought were absent in the typologies found in the literature. In addition, the expert workshops together with relevant literature were used to identify which of the methods were amenable to representing the attributes of coupled natural and human systems earlier selected. Finally, the section on insights from psychological and social sciences regarding these attributes was developed through non-systematic literature review across social science disciplines of sociology, psychology and human geography.

3.1. Identifying the attributes of coupled natural and human systems

Within the framework of interactions between human and natural systems, House-Peters and Chang [77, and references therein] identify the following four themes to reflect such dynamics: scale, uncertainty, nonlinearity and dynamic processes. Other studies [54,78] identify further themes that may need to be captured by research methods exploring longer-term future demand for energy and water: systemic change, stochastic events, path dependency, people's behaviour, policy interventions, emergent qualities, infrastructural changes, temporal scales (*e.g.* short-, medium- and long-term) and spatial levels (*e.g.* local, regional, national and global), as well as interactions between these attributes.

Many of these themes are highly intertwined and insufficiently specific to be useful for improving a model's ability to represent rapid and systemic change. To short-list attributes useful for the purposes of this paper, the following three criteria were used. Firstly, each attribute should correspond to one of the key drivers of the paradigm shift identified in the Introduction. Secondly, each selected attribute should be distinct, *i.e.* not have significant overlaps with the other selected attributes. Finally, an attribute should be specific enough to be usefully defined and provide variables[2] that can potentially become part of a modelling environment. Each of the themes in the previous paragraph were qualitatively scored against these three criteria, and the four attributes eventually selected (Table 1) were given new names to distinguish them from the themes identified in the literature. The attributes were then used as an analysis framework when evaluating how well the methods in the typology (Fig. 1) integrated those attributes.

3.2. Development of a typology of demand-focused methods

Following the development of the attributes, a systematic literature review of peer-reviewed journal papers on methods of demand modelling was conducted, in order to identify those that may fulfil the attributes and work across nexus boundaries. The aim was to develop a comprehensive typology of demand-based methods across energy and water studies, with a focus on exploratory methods suitable for long timeframes. The databases and search engines accessed included Scopus, Google Scholar and Science Direct. Scopus (719 hits) was used as the main search engine, given that it captures the majority of peer-reviewed journals in the relevant areas. Google Scholar then helped to identify relevant grey literature *e.g.* reports that also presented typologies. The search keywords covered combinations of 'typology', 'forecasting', 'forecast', 'prediction', 'predicted', 'demand', 'energy', 'power', 'electricity', 'water', 'future', 'behaviour'/'behavior' and technique names such as 'agent-based modelling' (see Fig. 1) used with Boolean operators 'AND' and 'OR'. The search keywords were determined by the research objectives of this study discussed in the introduction and literature review sections.

The primary selection criterion was that each study should present a typology for exploring future demand in the area of either energy or water, rather than the application of a particular method. The studies that contained typologies or taxonomies of anything other than methods for exploring future demand (*e.g.* a typology of skills or a taxonomy of compensating customers in the energy industry) were excluded. A general selection principle was saturation, representing a point at which further literature search stopped contributing new insights to the creation of a comprehensive typology of energy and water demand futures modelling methods. In total, six peer-reviewed typologies (cited in the caption of Fig. 1) were selected and combined into an aggregate typology presented in Section 5. To this end, we applied a 'framework synthesis', which required the establishment of a framework in advance of synthesising the literature, while keeping the framework flexible in order to absorb new findings [79]. In our case, this *a priori* framework had been based on an expert survey of 13 interdisciplinary scholars across the University of Manchester who were engaged with energy and water demand research. Participants were recruited by email, telephone and in person from across the physical and social sciences, including engineers, computer scientists, economists, human geographers, sociologists, and psychologists. The survey used the SurveyMonkey platform and had a 100% completion rate *i.e.* all 13 experts responded.

The survey generated data on the range of techniques, methods and data sources used to understand the future energy and water demand by researchers from different disciplines. The survey included questions on the advantages, limitations and uncertainties of each of these methods alongside questions on how data was analysed and used. Particular attention was paid to the representation of 'behaviour' across the disciplines, and the conceptualisation of 'demand'.

The typology was then further developed and refined during two interdisciplinary expert workshops. The workshops were conducted to

[2] A 'variable' in a modelling context would be a placeholder (usually denoted by an alphabetic character such as x or y) that can assume a given quantitative or qualitative value in a model.

discuss and validate the findings of the survey and the emerging typology (workshop 1), and explore which methods were employed, or under-used, within non-academic water and energy sectors (workshop 2). The first workshop included the respondents that took part in the expert survey, whereas the second workshop engaged both academic and non-academic stakeholders who applied modelling techniques to the UK's energy and water industries. During the first workshop, participants critiqued a survey-informed version of the typology and contributed several methods to it, such as the Delphi method, multicriteria decision analysis, and meta-analysis. The second workshop helped to identify knowledge gaps relevant for practitioners. During this workshop, the non-academic stakeholders' contribution was in verifying whether certain methods of exploring future demand were under-used in the private sector (in addition to academic literature in this field). The stakeholders were selected based on their long-term experience and the authors' contacts in the energy and water sectors.

Finally, examples of each of the methods in the developed typology were identified through a narrative literature review. In this instance the key selection criterion was that each study should use a particular method in Fig. 1, or a combination thereof, for exploring future demand in the area of either energy or water. Recent examples of modelling methods *i.e.* those published since 2000 were predominantly selected (34 studies), although in two instances older studies were chosen where more recent relevant work could not be identified.

4. Attributes of coupled natural and human systems under deep uncertainty

The ongoing paradigm shift and the need to inform planning in the medium to long term present a challenge to existing decision-support models and tools. It is essential for both demand-related research and policy that modelling reflects these uncertainties and dynamics. To achieve it, this section explores what qualities (termed here as 'attributes') of the human and natural systems [75,76] can help to represent uncertainty of future demand in planning and decision-support tools for the energy and water sectors.

Based on the literature and selection criteria considered in the methods section, four attributes have been identified, named here as 'stochastic events', 'diversity of behaviour', 'policy interventions' and 'co-evolution'. Table 1 summarises the sources of uncertainty captured within each of the four attributes and gives examples of variables related to those attributes that can help to explore energy and water demand under conditions of deep uncertainty. The first three attributes include examples that can be categorised as input variables for models (see the final column of Table 1), while 'co-evolution' covers key relationships between the variables ensuring that those relationships are not simplified to the extent where the reality is compromised. Relationships between the attributes include, for example, the effects that policy interventions can have on technological breakthroughs and on practices, or the ways that diversity of behaviour drives social unrest or changes in service provision.

The unpredictability and randomness element relates to the first of the four selected attributes, 'stochastic events' – a concept that climate change science borrows from statistics. This term usually refers to climate change impacts that are difficult to predict, such as extreme weather events that may cause immediate disruptions and fluctuations in the energy and water supply. House-Peters and Chang [77] contrast stochastic events with changes in income and demographics that tend to influence demand gradually, with the impact being spread across several years. Stochastic events can be reflected in models as system shocks whose effect may be either one-off or lasting. Examples of variables for 'stochastic events' to be represented in models include a stochastic (as opposed to deterministic) representation of climate change impacts, technological breakthroughs or social unrest.

The second attribute is the 'diversity of behaviour'. This paper adopts the concept 'diversity of behaviour', rather than 'individual behaviour', with the intention to capture behavioural patterns at a systems level. Such patterns arise because particular ways of doing things are embedded within the surrounding systems *i.e.* infrastructures, institutions, social norms and the rule of law [80]. This concept reflects the diversity of people's actions in relation to the resources they consume, and why. Explanations for why people engage in particular forms of resource consumption vary substantially along theoretical and disciplinary lines (further discussed in the 'Insights from social science approaches' section below). Examples of variables for 'diversity of behaviour' to be represented when modelling future demand include such impacts on demand as social networks exerting group/peer pressure; attitudes towards energy and water conservation; social practices related to the dynamics of everyday life; the diffusion of information and consumer classifications *e.g.* 'early adopters' of technology.

'Policy interventions' is the third attribute identified here. This attribute is broader than the first two as it can contribute to nonlinearity, produce new system dynamics, and partly capture infrastructural change and systemic transformation. The challenge is to establish how long the effect of policy interventions would last, how it would percolate through the system, what other elements of the system would be affected, and what feedback loops would emerge. These questions are also valid for the first two attributes and are explicitly captured in the final attribute, 'co-evolution'. Examples of variables for the 'policy interventions' attribute are standards for fuel and water efficiency, a feed-in tariff or a carbon tax.

This paper defines the fourth attribute, 'co-evolution', as the way that infrastructures, technologies, institutions and practices jointly develop in a nonlinear manner over time. The concept of co-evolution is to capture key interactions, relationships and feedback loops between variables specified within the previous three attributes (*i.e.* stochastic events, diversity of behaviour and policy interventions). In particular, a feedback loop arises when some of the information about a process is fed back to a starting point of the process, affecting that starting point; *i.e.* the response of a system affects inputs into that system. Socio-economic systems display various aspects of co-evolution. For example,

Table 1
The four attributes of socio-natural systems with examples of variables that models could represent as proxies for sources of uncertainty.
Source: own analysis.

Attribute	Sources of uncertainty captured	Examples of variables to be represented in models
Stochastic events	Unpredictability, randomness, qualities arising unexpectedly.	A stochastic (as opposed to deterministic) representation of climate change impacts, technological breakthroughs, social unrest, economic crises.
Diversity of behaviour	Human behaviour (from individual behaviour to behavioural patterns and practices at a population/systems level).	Social networks exerting group/peer pressure; attitudes towards energy and water conservation, consumer classifications, diffusion of information, social and cultural norms.
Policy interventions	Planned 'shocks' with unpredictable, particularly unintended, consequences.	Standards for fuel and water efficiency, a feed-in tariff, a carbon tax, changes in levels of service provision.
Co-evolution	Interactions and feedback loops, path dependency, emergence, temporal scales, non-linear developments.	Key relationships and interactions between the variables specified within the other three attributes.

supply and demand are said to co-evolve when increasing supply leads to a disproportionate increase in demand through raising people's expectations of a service [81,82]. These expectations exist at the societal, rather than individual, level and create multiple flow-on effects in related sectors. Similarly, the rise of showering as the dominant way of achieving bodily cleanliness in the UK [83] reflects the co-evolution of household technologies, wider systems of infrastructure and social norms and expectations for cleanliness and comfort [84]. With socio-economic systems being strongly coupled with biophysical systems, they constantly co-evolve and adapt to ongoing changes [85]. At the very least, modelled variables within the 'co-evolution' attribute should attempt to capture interactions and feedbacks between new technologies, policy interventions, the changing climate and the diversity of emerging behaviours.

5. A typology of demand-focused methods in the water and energy sectors

Before assessing how existing methods can represent the four attributes identified so far, this subsection consolidates method typologies from the literature, the expert survey and the first workshop, to help broaden the 'menu' of methods available. The new comprehensive typology (Fig. 1) devised for the purposes of this paper draws on the method classifications frequently applied to studying both energy and water demand. Such classifications typically address a particular area of application (either water or energy) within a specific time horizon (short, medium or long term); however qualitative and mixed methods are often not well represented. This research finds that studies of both future water and energy demand rely on broadly similar modelling methods and explore comparable timeframes. Typical classifications [77,86] are dominated by methods from two main groups named here as 'traditional statistical/mathematical methods' and 'machine-learning methods', occasionally adding some qualitative or mixed methods, such as the Delphi technique and conceptual models.

In the new typology (Fig. 1), the integrated method classifications from the literature are augmented with complementary qualitative and mixed methods such as multicriteria decision analysis and transitions theory, as discussed by the experts on demand modelling at the workshops. The 'Misc.' (miscellaneous) branch of the typology has been created based on Bhattacharyya [87] who classifies methods for energy demand forecasting into 'simple' and 'advanced'. He covers both end-use and input-output modelling in the advanced group, alongside econometric models that are included here in the 'traditional statistical/mathematical methods'. Examples of his 'simple' methods are trend analysis and direct surveys. The only qualitative or mixed method Bhattacharyya [87] suggests is scenario analysis. In general, his simple-*vs.*-advanced classification is insufficiently detailed for the purposes of this paper, as this classification does not reveal the principles that underlie particular modelling methods (*e.g.* whether it is simple mathematics, or mathematics combined with qualitative methods and requiring significant computing capacity, or a combination of simple qualitative and quantitative methods). While his classification is not adopted here, the methods discussed by Bhattacharyya [87] are included in the typology in Fig. 1.

Memon and Butler [88] offer an alternative classification of methods for forecasting water demand, implying a direct correlation between time horizons and data intensity. They argue that long-term forecasting requires conceptual techniques and relatively little data, while short-term forecasting calls for data-intensive methods [88]. Their short term appears to refer to hourly and daily forecasting; and, although they do not define 'long term' explicitly, their example of scenario 'prediction' refers to 2025 [88]. Examples of methods are given that "were designed to make *long-term* predictions" [88], such as statistical methods, "scenario-based forecasting" and forecasting methods for "network operations". Memon and Butler's [88] idea that exploring long-term future demand may need to go beyond quantitative modelling is consistent with the diversity of methods presented in Fig. 1 (for example, 'conceptual models' are captured in the 'Qualitative or mixed methods' part of this new typology).

The elements of the typology are neither uniform nor clearly demarcated by scope and purpose, indicative of the complexity of managing resources at the nexus. The key groups of methods overlap substantially: regression methods draw on time-series analysis, while machine-learning methods draw on both statistical and qualitative methods. Other overlapping methods include agent-based models that combine qualitative and quantitative approaches [49,77]. Generally, qualitative methods, in addition to being used in a stand-alone fashion, are often applied in combination with the other three groups [92–94].

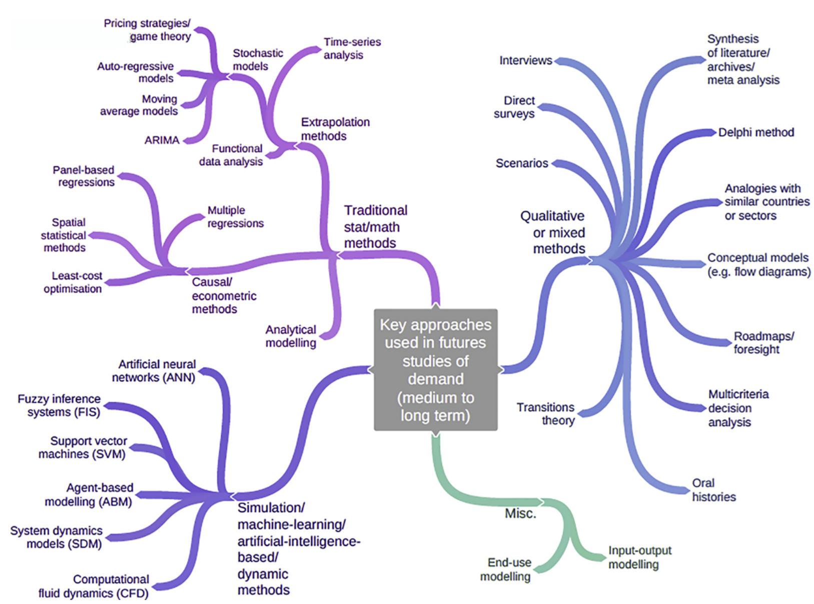

Fig. 1. A comprehensive typology of methods used in studies of future energy and water demand. Sources: based on [77,86,87,89–91] and on the results of the expert survey and two interdisciplinary workshops that took place in June and September 2014.

For example, some of the qualitative methods are ways of gathering data (*e.g.* meta-analyses, direct surveys and Delphi methods); others are systems of ideas for framing the analysis of future demand (*e.g.* transitions theory); yet others are applied to modelling tools (*e.g.* scenarios). The term 'scenarios' here refers to a particularly broad concept: they are extensively used in futures studies in combination with virtually all methods listed in the typology. For example, Memon and Butler [88] view scenarios as another forecasting technique, which is contested according to the original and commonly used definition of scenarios stating that they are non-predictive [95–97].

On balance, traditional statistical methods are still the most common in futures studies, particularly forecasting, despite machine-learning methods often having more accurate predictive capacity both in short and longer terms [86,98,99], due to the ability of machine-learning methods to better incorporate systemic complexity and interactions. The prevalence of traditional statistical methods confirms the bias in the way research questions are asked with an in-built agenda [100] – something that Asdal [101] calls a "shared technical interest" to solve a problem by generating a number.

The studies reviewed are not always explicit about defining the timeframe used. Their short-term time horizon varies from real-time to daily to monthly forecasting, while long term is "one to ten years, and sometimes up to several decades" [98]. The next subsection will explore how suitable the methods summarised in Fig. 1 are for informing strategic planning, bearing in mind the infrastructure lifespan and significant climate change impacts that will be observed towards the end of the century.

6. The suitability of key demand-focused methods to supporting strategic planning

The Introduction discussed the dynamics and conditions of uncertainty that should underpin emerging research methods to explore future demand for energy and water. Following the translation of the uncertainties into the four attributes (Table 1), this subsection analyses the ability of existing methods summarised in Fig. 1 to capture, at least to some extent, these dynamics. As a caveat, only typical rather than potential applications of the methods to the four attributes are discussed here. This is because, theoretically, machine-learning methods in particular have almost unlimited possibilities if they are applied unconventionally, further developed and/or combined with qualitative or other machine-learning methods [102].

According to the typology literature analysed here, 'policy interventions' is the attribute that most methods try to incorporate [102,103], followed by 'stochastic events' [104,105]. Among the traditional methods, it is the stochastic models [105–109] that include these attributes, while causal [110–114] and extrapolation [115–117] methods appear unable to do so. However, even within the stochastic methods, consequences of policy interventions tend to be modelled in a linear way, with little regard for the 'ripples' throughout the system (*i.e.* consequences of events propagating through the system in unexpected and non-linear ways). Machine-learning methods [116,118–123] are reported to be more suitable for taking into account the dynamics and nonlinearity [77]. These qualities might make machine-based methods even more useful for strategic decision-support than for prediction [78], which they tend to be used for. Difficulties for both types of methods arise when capturing unintended consequences of policies, as well as when identifying whether policy interventions and stochastic events are lingering or one-off events.

The diversity of behaviour is another attribute addressed with varying levels of success. Similar to policy interventions, some of the methods incorporate it in a reductionist way. For example, stochastic models use dummy variables to reflect such aspects as gender, race or age groups, whereas least-cost optimisation accounts for the diversity of behaviour *via* 'rules' and 'preferences'. These traditional methods usually pre-set behaviour based on the 'rational choice' theory [124–126]. By contrast, agent-based modelling is designed to let behaviour patterns emerge as a result of individuals' interactions with each other and with the environment. The attribute least represented within the reviewed methods is co-evolution. Only machine-learning methods attempt to integrate aspects of co-evolution in the form of feedback loops and interrelationships between variables.

The literature [*e.g.* 98,127–129] emphasises the limits of traditional modelling in application to longer-term (beyond ten years) and systemic issues. With the ongoing 'paradigm shift' in mind, machine-learning methods emerge as more appropriate for this purpose, owing to their ability to capture dynamic processes, nonlinear interactions and behavioural patterns [77,86]. At the same time, their disadvantages include their complexity and data intensity that can compromise the transparency of the models and obscure the interpretation of results [77,86]. Of particular interest are the participative methods among the 'Qualitative or mixed methods' category in Fig. 1, including interviews and the Delphi method; literature suggests that appropriately engaging with stakeholders opens up new ways of exploring futures [130,131].

Problems may arise when specific methods claim to have a purpose they are not designed to deliver while continuing to inform both policy and practice. An example of this issue is the UK Water Industry where in the latest 25 year planning exercise stochastic modelling was used for the first time to explore supply side planning, but the demand side is still resolved with deterministic models *i.e.* extrapolation [132]. In the energy sector, a similar example is optimisation-based Integrated Assessment Models used for the long-term study of energy systems [133]. Such models are inadequate for the purpose of supporting long-term decision-making under conditions of deep uncertainty and risk misleading non-expert users of these studies.

The issues discussed in this section relate to one of the main aspects of complex systems – uncertainty. Futures studies (*i.e.* studies that explore futures) deal with uncertainty by introducing sensitivity analysis, scenarios and probability distributions, and by drawing on other disciplines and qualitative approaches, such as expert review. Some futures studies and modelling approaches regularly attempt to represent policy interventions and stochastic events. However, the 'diversity of behaviour' and 'co-evolution' perspectives are under-conceptualised in modelling current and future demand. The next section draws on disciplines that could inform the integration of these two attributes into the wider modelling literature. While demand studies in general can consider changing demand of a range of actors (for example, householders, communities, farmers and businesses), here two bodies of literature are explored that have specifically focused on household demand and were highlighted during the expert workshops. Both psychological and sociological sciences emphasise the social, or demand, side that has long been neglected in favour the technologies and the supply side [134,135]. At the same time, these two relatively distinct sets of literature speak in different ways to the understanding of uncertainties presented in Table 1, and to planning and managing water and energy resources. The forthcoming section is not intended as a comprehensive review, but rather tentative ideas on how mainstream and largely quantitative modelling methods can learn from other research areas.

7. Insights from social sciences: cross-disciplinary learning

7.1. Perspectives from social psychology

One prevailing approach to understanding demand has focused on the individual as a unit of analysis and employed models that seek to understand pro-environmental behaviour and motivations, and their impacts on energy and water demand [136–139]. This approach typically explores how attitudes, beliefs and values shape human behaviour, with a focus on the individual's agency. The rational choice model and theories of planned behaviour and reasoned action represent individuals as independent decision-makers. Others, such as the norm activation model, allocate a level of agency to social norms, as a person's behaviour is influenced by their awareness of the consequences of their actions and their acceptance of personal responsibility [140].

Although this literature increasingly acknowledges the attitude-behaviour gap in relation to environmental decision-making [139], the rational choice model has been influential in both environmental economics and policy [*e.g.* 126] (see [100] for a succinct discussion of why this model dominates). This view is linked to the information-deficit model: to make rational choice, individuals need to be provided with information to assist them with their decisions. This approach is useful for identifying drivers to behavioural change [140], exploring routines and conventions of resource use [141], and factoring in 'rebound effects' [142]; for instance, if a person is motivated by values rather than by money to implement an environmental measure, the rebound effects might be smaller [143]. The elements of the MINDSPACE framework (Messenger, Incentives, Norms, Defaults, Priming, Affect, Commitments, Ego) developed for influencing behaviour through policy are another example of potential inputs in decision-support modelling [144].

Several criticisms have been levelled at these approaches to resource use and pro-environmental behaviour. Jackson [124] argues that they assume 'methodological individualism', where social behaviour is understood to be the result of an aggregation of individual behaviours. The focus on individuals and the relative decline of group research has been noted historically [145], although organisational psychology has since started unpacking group dynamics of work teams and tracing the impacts of adopting energy-related behaviours in workplaces [146,147]. However, research on resource consumption at this level of analysis is relatively limited [148]. Therefore, the risk of modelling future demand from this perspective is that demand at a population level is seen as a multiplied effect of individual decisions, divorced from system-level constraints. For example, in relation to the attributes outlined in Table 1, these theories struggle to analyse changes in behaviour arising from stochastic events, or to explain behaviour from the perspective of the co-evolution and interaction of demand and wider factors. Demand is thus explored in a deterministic way, with the actions of the individual isolated from their cultural or socio-technical contexts. While several psychological studies include contextual determinants such as socio-demographic variables in their models [140,149], this understanding of the social and physical context is different from the interactive and relational dynamics [150] uncovered by the 'co-evolution' approach.

7.2. Perspectives from sociology and human geography

Given the criticisms directed at the psychological perspective, demand-related developments within sociology and human geography have been positioned as alternatives [100,151]. These approaches have emphasised the material and social structures implicit in processes of consumption, highlighting the way that technologies, infrastructure, social norms and practices co-evolve across space and time [152–156]. Such perspective provides insight into the processes underpinning historical and current demand for water, energy and other resources. This insight includes reflections on the social nature of demand (*i.e.* emerging societal norms on cleanliness, health and thermal comfort), the material nature of demand (for example, the infrastructures and technologies linking production and demand), and how demand 'is done' in peoples' day-to-day lives (*i.e.* the ways that these practices are expressed). It provides insights into the diversity of behaviour (practices as framed in this literature) as understood at a population level. These perspectives also contribute strongly to understanding how demand co-evolves in relation to social, cultural and infrastructural elements, and as a result of policy interventions (Table 1).

The focus of sociological and human geographical approaches, together representing the main locus of social science research on energy and water demand, is on how context (*e.g.* space, place, time) and structures (material or cultural) give rise to practices, characterised by the co-evolution attribute described in Section 4 [157,158]. In particular, such disciplinary perspectives are attentive to notions of *difference and unevenness*, within and across societies and space [159]. Work on energy justice [160–162] highlights the complex historical and geographically specific constructions of energy production and distribution, and how these socio-material histories "may be limiting the current conditions and choices for ethical and sustainable consumption" [160]. The notion of ethics in this literature also extends to intergenerational equities [163] and the gendered politics of research on demand and climate change [164].

In relation to futures modelling, this research emphasises that the past-present-future is not an evenly shared or homogenous entity to be modelled as a singular 'demand' outcome [165]. The challenge for futures studies is to understand how the water and energy supply-demand systems vary across time and space [82,166]. One could consider a framework of services, for example how water and energy resources satisfy human and environmental needs [167,168]. What is considered a need also changes over space and time [154]. A focus on services enables policy and scientific discussions to shift from the supply of the resource to the effects [168,169]. Thinking about services re-focuses analysis on how complex systems may co-evolve to meet and create diverse demand effects. Although the co-evolution is methodologically challenging to capture, some recent methods attempt to consider these diverse socio-material entanglements, through backcasting and transition planning of resource use [170,171], developing a population-level understanding of practice-based changes [169] and including practice theory in agent-based modelling [74].

8. Conclusions

Strategic planning of energy and water provision has long-term and far-reaching consequences, as the long lifespan of these infrastructures shapes patterns of demand and consumption for decades ahead. From this perspective, demand appears relatively fixed; however, the ongoing major changes in climate, society and technology create an increasingly dynamic environment with manifold effects that themselves interact to drive demand in different ways. This transformation is particularly pertinent to energy and water resources, where future demand ought to be explored under conditions of rapid change and deep uncertainty [3]. This paradigm shift requires new types of research questions and, accordingly, new ways of answering those questions [100].

To inform strategic planning in the water and energy sectors, the interdisciplinary demand literature has called to clarify these uncertainties, both conceptually and methodologically. However, there has been little reflection on how 'demand studies' on water and energy represent the uncertainties, and the area has been dominated by mainstream, quantitative economics. To address this lack of reflection and to highlight a wider range of methods available, this paper has developed a comprehensive typology of methods for exploring future energy and water demand. After identifying the four attributes ('stochastic events', 'diversity of behaviour', 'policy interventions' and 'co-evolution'), the paper posits that methods should be able to represent or capture deep uncertainty; and has provided examples of how insights from psychological and social science disciplines can assist in conceptualising these uncertainties.

The analysis in this paper has a number of limitations raising further questions for researchers, policy-makers and industry. In particular, questions arise as to whether these uncertainties (as attributes presented in Table 1) can or should be quantified and whether there are other ways to take them into account in a way that supports more responsive and effective planning about demand/supply systems. One challenge is whether to integrate the uncertainties represented in the attribute 'co-evolution' in existing methods, or to keep it as part of the context. Another example is given by Kandil et al. [86], who warn that in fast-developing systems, such as electricity grids in industrialising economies, many events are unpredictable and not currently quantified, while existing models still cannot accommodate such information (*e.g.*, the liberalisation of the sector). This offers a question for future research and international decision-making as to whether demand-related models developed for industrialised countries can be applied to the context of industrialising countries with different policy and regulatory systems [172,173].

The challenge for research on futures studies (*i.e.* studies that explore futures) for the nexus of energy and water demand is two-fold: whether, and how, methodological approaches to future studies capture complexities and co-evolution, and how more sophisticated futures studies can be used by policy makers and decision makers. Demand-modelling methods are designed for various purposes (*e.g.* to reveal surprises and complexity, to characterise possibility space or to provide forecasts) and different scales and scopes (*e.g.*, global, local, a systemic/integrated problem or a single issue) [174]. Future demand is just one element of the information taken into account by decision-makers when planning new infrastructure. Decision-makers are often presented with a range of investment options with respect to infrastructure development within the context of deep uncertainty that renders optimisation techniques that rely upon known values and probabilities impractical [127]. Accordingly, new ways of engaging with the complexities and uncertainties (co-evolution) are needed to prepare our supply-demand systems in a way that is 'resilient' to future climatic and other social/technological changes.

Given that both 'diversity of behaviour' and 'co-evolution' are currently under-represented within the modelling literature, it is important to reflect on the nature of this conceptual and empirical gap and opportunities for further integration. The lack of application of these approaches in interdisciplinary research on the water-energy nexus is partly due to how the future, and the scale of analysis, is conceptualised in the majority of modelling literature. For example, co-evolution approaches consider the future to be emergent and changeable [169,175,176], even though history continues to have some influence on the future, such as infrastructure legacies. By contrast, modelling perspectives largely carry forward historical configurations as the baseline for the future. Histories of relationships between infrastructures, social factors and practices have shown that the precise configuration of 'future practices' is in itself unpredictable. The literature engaging with ideas about co-evolution does enable a different set of questions to be asked about the implication for demand of material, social and policy investments in the water and energy sectors. While they have not been applied in any systematic way to futures studies and demand modelling, it does not mean that it cannot be so. The challenge for the researchers and modellers working in the areas of energy and water demand is to experiment with new conceptual and methodological resources that accommodate such dynamic uncertainties, unevenness and complexities.

The analysis of current methods highlights that no single method is able to meet all the attributes of stochastic events, diversity of behaviour, policy interventions, and co-evolution. Instead, a combination of both quantitative and qualitative methods may genuinely be able to address the four attributes of deep uncertainty. Such whole-systems approaches should ideally reflect the nexus thinking across the energy and water sectors, and be enhanced with interdisciplinary insights. This would change the balance of modelling from focusing predominantly on technology and isolated individuals towards systems thinking. For example, combining simulation models with participative methods (such as quantitative and qualitative engagement of stakeholders) would provide more information about people's interactions with the system, better reflect the complexity of the real world, and potentially increase buy-in for infrastructure projects [177].

The principal disadvantage of combining or even integrating different methods is that it can be expensive, time-consuming and logistically challenging (for example, when gathering advice from international experts). In addition, some insights from sociology and human geography may baffle policy-makers [124], as quantitative outputs of traditional models are arguably easier to convert into policies, thereby perpetuating in-built agendas of dominant methods [100] and avoiding systemic changes. However, ultimately the aim of broadening the range of social science methods in use is to address the paradigm shift through challenging the current "shared technical interest" [101] of both policy and methods in producing incremental change.

Rather than attempting to *predict* the future and then plan accordingly, methods should seek to assess and challenge policy and planning options in relation to pertinent parameters (*e.g.* climate impacts, capital and operational costs, legislative and environmental factors, socio-cultural shifts, in addition to future demand and supply information) with the aim to identify strategies which are robust to the uncertainties within these parameters. In particular, it is necessary to represent future demand through multiple plausible futures reflecting the unevenness of the futures and their emergent nature. The challenge for those investigating future demand under these circumstances is to capture as far as is reasonable a range of both quantitative and qualitative characteristics of demand including extremes, not solely a 'best estimate'. The ranges of futures derived need to be regularly reviewed and adapted, as new data and circumstances arise. In summary, considering a range of futures, involving stakeholders and adaptivity are essential for improving the ability of futures studies to envision surprises and inform planning and long-term policy-making across the energy and water sectors.

Acknowledgements

This research was funded by the University of Manchester Research Institute (UMRI). We would like to acknowledge the interdisciplinary academic participants of our first workshop on 'Mapping Expertise in Water and Energy Demand Research across the University of Manchester' on 25 June 2014 who commented on and added to the typology of future studies for energy and water demand presented in this paper. With thanks to John Moriarty, Ben Anderson, John Brooke, Paul Dewick, Paul Gilbert, Ralitsa Hiteva, Zehui Jin, Richard Kingston, Alexandros Maziotis, Hazel Pettifor and Thomas Roberts, for the valuable contribution to the workshops and discussions that have informed our thinking within this paper. Additional thanks to our facilitators Gill Fenna and Louise Marix Evans.

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